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ICE BREAK-UP ON NORTHERN RIVERS: THE LIARD RIVER AS AN EXAMPLE

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MANAGEMENT PERSPECTIVE

This paper was produced in response to a request from the organisers of the "Knowing the North Conference: Northern Lakes and Rivers Workshop" to describe the major physical processes which characterise ice break-up on large northern rivers. Given the multi-disciplinary nature of the workshop, the report was written in general terms to permit interaction among a wide range of scientists and to maximise readership, although references to the detailed scientific literature are also included. This report, which uses the Liard River - one of the most intensely studied rivers in northern Canada - as an example, should provide a sound introduction for other scientists and engineers interested in ice break-up on northern rivers.

PERSPECTIVE DE GESTION

Les organisateurs de la «Knowing the North Conference: Northern Lakes and Rivers Workshop» ont demandé la rédaction d'un rapport pour décrire les principaux phénomènes physiques qui caractérisent la débâcle dans les grands cours d'eau du Nord. Comme il s'agissait d'un atelier de nature pluri-disciplinaire, le rapport a été rédigé en termes généraux; de cette façon, l'interaction entre un grand nombre de chercheurs est réalisable et le plus grand nombre possible de lecteurs peuvent en prendre connaissance, même si des renvois à des publications scientifiques sont également donnés. Le rapport, fondé sur des études faites dans la rivière Liard - l'une des plus étudiées dans le Nord - devrait fournir une bonne introduction aux autres chercheurs et ingénieurs qu'intéresse la débâcle dans les cours d'eau du Nord.

ABSTRACT

The major hydromechanical and hydrothermal processes which control ice break-up on northern rivers are reviewed. The Liard River, one of the more intensely studied northern rivers, is used as the primary example. Break-up of the Liard is especially significant because it "triggers" that of the Mackenzie River, Canada's longest river and one of the world's largest ice-covered rivers. According to combinations of river discharge and ice strength, six years of break-up are classified into thermal and mechanical events. Mechanical events produce the most dramatic form of break-up, characterized by break-up fronts moving at speeds in excess of 5 m/s and the formation of ice jams, 4-8 m thick and 10-22 km long. The results of an equilibrium jam analysis for the development of a jam stage-discharge relationship are reviewed and suggestions for future research needed to achieve flood-damage reduction on northern rivers are presented.

RÉSUMÉ

Les principaux phénomène· hydromécaniques et hydrothermiques qui commandent la débâcle dans les cours d 'eau du Nord sont examinés. La rivière Liard, l'une des plus étudiées dans le Nord, sert d'exemple principal. La débâcle dans la Liard revêt une importance particulière du fait qu'elle déclanche celle du Mackenzie, le plus long fleuve au Canada et un des plus grandsau monde à être recouvert de glace en hiver. D'après les données sur le débit de la rivière et la résistance de la glace, les débâcles de six années sont classifiées en manifestations thermiques et mécaniques. Les manifestations mécaniques donnet lieu à la forme de débâcle la plus spectaculaire, caractérisée par des fronts qui se déplacent à plus de 5 m/a et à la formation d'embâcles de 4 à 8 m d'épaisseur sur 10 à 22 km de longeur. On passe en revue les résultats d'une analyse d'équilibre des forces d'embâcle pour l'établissement d'une relation entre le niveau de l'eau dû à l'embâcle et le débit du cours d'eau; des suggestions sont présentées afin de définir les travaux qui devront être effectués pour réduire les dommages causés par les inondations des cours d'eau du Nord.

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INTRODUCTION

River ice break-up can be a spectacular process, capable of modifying the biologic, geomorphic and hydrologic regimes of rivers and severely affecting man's related activities. The annual cost in Canada of ice jams alone has been estimated by Atkinson (1973) to be $31,000,000 (1983 dollars, see Prowse, 1985a). The most dramatic and potentially damaging break-ups occur on northward flowing rivers or rivers in which break-up first occurs in the headwaters and then moves progressively downstream, following a downstream warming created by prevailing weather patterns. Examples within northern Canada include the Yukon and Mackenzie, which are characterized by break-ups originating in southern regions and advancing into the colder higher latitudes, and rivers such as the Liard, Peace and Athabasca which have headwaters in the Cordillera and then flow into the colder continental interior. The 'warm to cold' pattern of break-up poses the most severe ice jamming and flooding problems because the spring flood wave is always having to push against a downstream ice cover. A much less dramatic form of break-up occurs on rivers which flow in a direction opposite to that of climatic warming. On south flowing rivers, for example, south to north warming allows ice clearance to work progressively upstream, thereby reducing the probability of ice jamming.

Although break-up has often been considered to occur at a single point in time, usually in relation to the first sustained movement of the ice cover, the entire break-up period is a continuum of often lengthy processes which first ablate, then fracture and finally convey the ice cover downstream. Assuming that the break-up period can be bracketed by the the first signs of ice deterioration and the time that the river becomes clear of floating ice, the mean duration of river ice break-up on Canadian rivers is 15.7 days (data from 102 rivers with >10 year record; unpublished data, Atmospheric Environment Service), although it can vary from as little as a few days to over a month. The duration of break-up is especially important to many northern communities because it often means a period of isolation without conventional transport by water or ice road.

Given that this conference has a multi-disciplinary theme of "Knowing the North", the objective of this paper is to describe in layman's terms the major hydromechanical and hydrothermal processes which characterize break-up on northern rivers. The Liard River, one of the more intensely studied northern rivers, will be used as the primary example. More detailed reviews of river

ice can be found in Ashton (1985) and Michel (1971) and a catalogue of case studies concerned with ice break-up on North American rivers in Petryk (1984, 1985).

SITE DESCRIPTION OF LIARD RIVER

Physical setting:

The break-up of the Liard River is especially significant because it "triggers" that of the Mackenzie River, Canada's longest river and one of the world's largest ice-covered rivers. Upstream of the Liard confluence, break-up of the Mackenzie River is primarily dependent on flow out of Great Slave Lake. Although southern tributaries, such as the Athabasca, Hay, Peace and Slave rivers contribute to the northerly flow of water, discharge from these basins is heavily damped by the stabilizing effects of Great Slave Lake (MacKay and Mackay, 1973a). Hence, break-up in the upstream portions of the Mackenzie River usually occurs later and is less spectacular than the break-up produced by the rapid spring run-off from the unregulated Liard catchment.

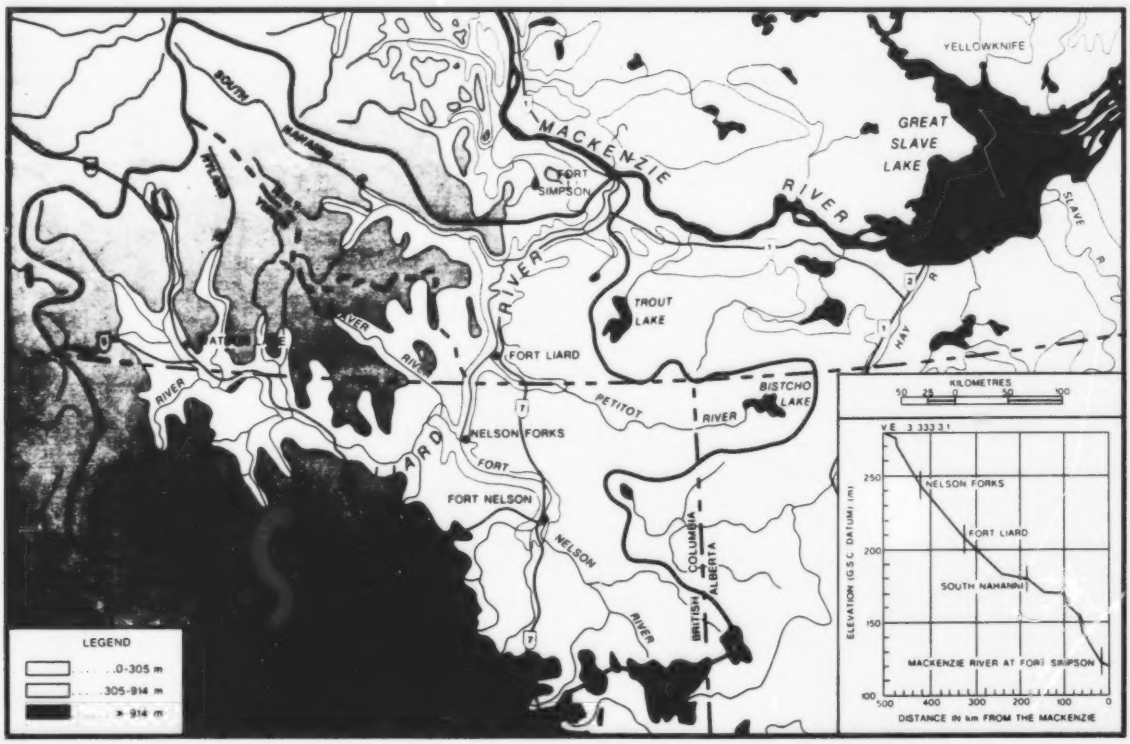

Fig.1. Liard River basin. River slope is shown in the inset (after Parkinson and Holder, 1982)

Draining an area of 277,000 km^2, the Liard is the largest tributary of the Mackenzie River downstream of Great Slave Lake. From its headwaters in the Cordillera, the Liard flows in a generally south-east direction until it meets the Fort Nelson River at Nelson Forks (Fig.1). From Nelson Forks, the Liard heads north-eastward across the plains of the Interior Plateau to its confluence with the Mackenzie River at Fort Simpson, N.W.T., a distance of approximately 430 km. Other major tributaries along the route include the Birch, Petitot, Poplar, and South Nahanni Rivers. During the ice-covered season, the Liard River contributes less than 20% of the Mackenzie River flow, although this percentage increases to between 25 and 35% during break-up and to over 45% in late May, after most floating ice has cleared (Prowse, 1984).

Spring Climate:

Upstream of Nelson Forks, the Liard River divides into a northern (upper Liard River) and southern (Fort Nelson River) catchment. As shown in Fig.1, much of the upper Liard River basin lies above 900 m and could be classed as alpine, whereas a large proportion of the Fort Nelson River Basin is lowland. The difference in elevation between the two catchments is reflected in their spring temperatures. The mean April temperature at Watson Lake in the upper Liard catchment is -0.6°C but that for Fort Nelson is +1.6°C.

In early spring, the southerly headwaters of the Nelson River are influenced largely by warm Pacific air masses, while the downstream and more northerly reaches of the Liard are affected by the colder more continental climate of the interior plains. A gradual influx of the warm westerly air replacing colder Arctic air produces a downstream gradient in springtime warming (Anderson and Fogarasi, 1981). The gradient is apparent in mean April temperatures which decrease by 1.8°C between Fort Nelson and Fort Liard, then by a further 1.3°C to Fort Simpson at the river mouth.

Snowmelt in the Liard catchment usually occurs first in the upstream tributaries of the Fort Nelson River and produces a corresponding rise in discharge. Rainfall in the spring months tends to be relatively low, and thus run-off is primarily snowmelt-generated (Anderson and Fogarasi, 1981). Fig.2 illustrates long term, mean discharges for the Fort Nelson River, three points on the Liard River and the Mackenzie River at Fort Simpson, during the April-May break-up period. Strong temporal differences are readily apparent in the onset of spring run-off among the stations. On average, discharge on the Fort

Nelson River begins to rise appreciably after the first week in April, followed by less pronounced rises in the lower reaches of the Liard River, as evidenced at Fort Liard and the river mouth. In contrast, that from the portion of the Liard River upstream of Nelson Forks does not begin to increase noticeably until late in April.

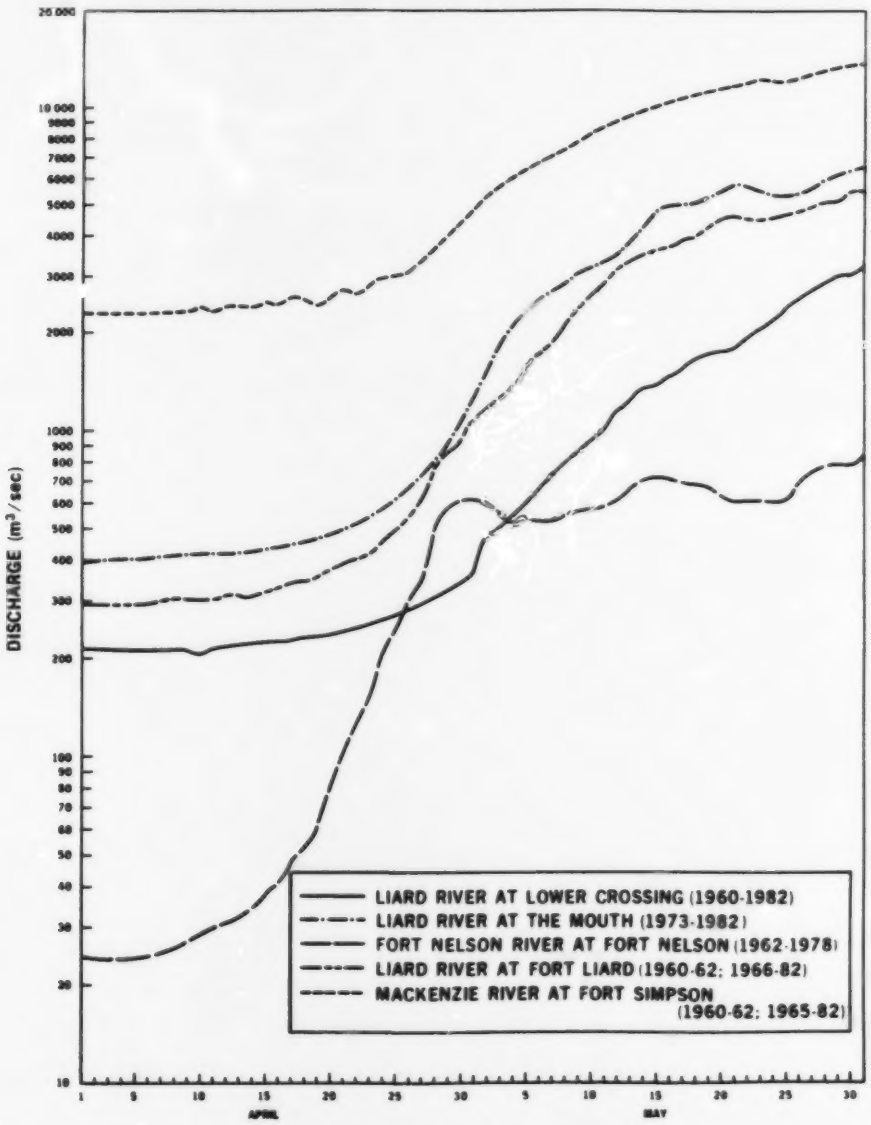
DISCHARGE (m³/sec)
LIARD RIVER AT LOWER CROSSING (1960-1982)
LIARD RIVER AT THE MOUTH (1973-1982)
FORT NELSON RIVER AT FORT NELSON (1962-1978)
LIARD RIVER AT FORT LIARD (1960-62; 1966-82)
MACKENZIE RIVER AT FORT SIMPSON (1960-62; 1965-82)
APRIL
MAY

Fig.2. Mean daily discharge during break-up. Length of records shown in brackets. 'Liard River at lower crossing' refers to lower crossing of the Alaska Highway, 59°24'N; 126°05'W. (from Prowse, 1984; Water Survey of Canada, unpublished data)

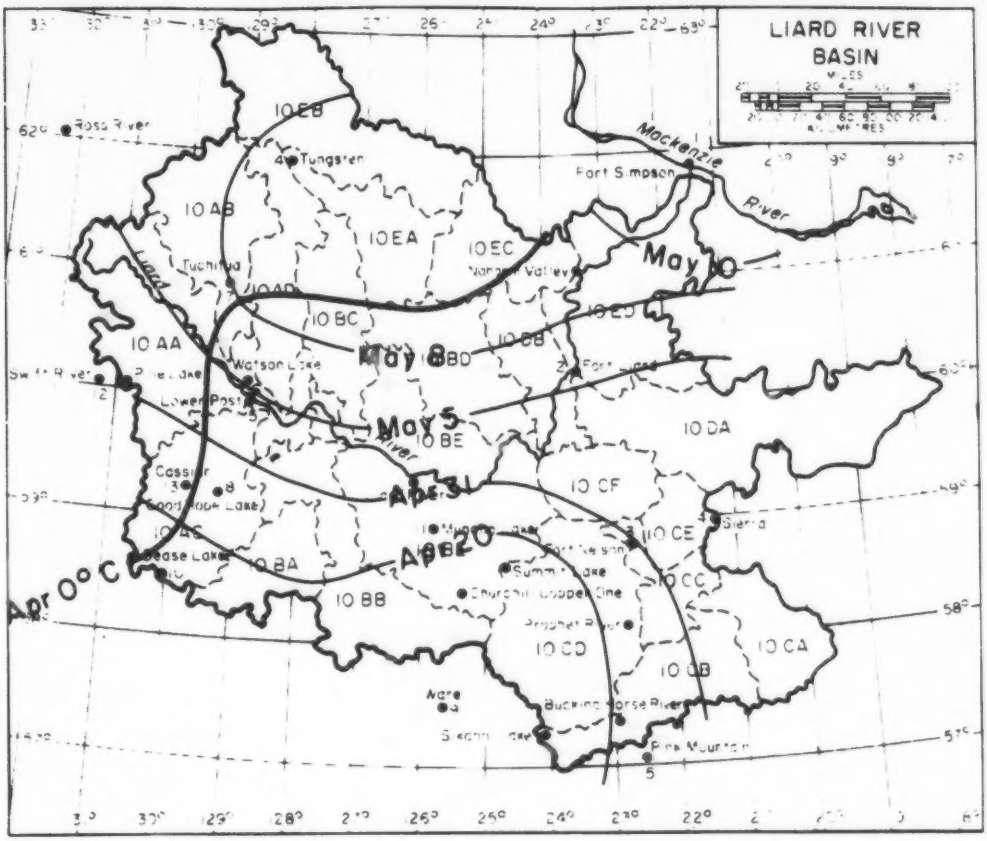

Fig.3. Mean isochrones of river ice break-up (1973-1977) and mean April 0°C isotherm. (from Anderson and Fogarasi, 1981)

Break-up pattern:

The large scale pattern of ice clearance on the Liard River is typical of most northward flowing rivers in which break-up originates in the headwaters and then progressively moves downstream. Fig.3 shows the mean isochrones of river ice break-up compiled from a 5-year record of 27 hydrometric stations (Anderson and Fogarasi, 1981). As illustrated, break-up usually occurs in the upper portions of the Fort Nelson catchment prior to April 20 and then passes downstream, reaching the Liard River mouth soon after May 10. Notably, break-up in the upper portions of the Liard catchment is retarded. For example, both Watson Lake in the upper Liard and Fort Liard, 100 km downstream of Fort Nelson, lie on the May 5 isochrone. Ice from the upper Liard is usually not part of the initial break-up front which passes down the Liard River, but rather comes down as a second wave of floating ice, sometimes even after ice clearance has continued into the Mackenzie River (Prowse, 1984).

BREAK-UP PROCESSES

Break-up processes are reviewed under four major headings: pre-break-up, break-up, ice jams and, water levels and discharge. The pre-break-up section contains generic descriptions of processes that are typical of most northern rivers. This section forms part of a review of river ice processes being prepared for the National Research Council of Canada (NRCC), Working Group on River Ice Jams. More site-specific data about the Liard River are used to illustrate the processes involved with break-up advance and ice jamming. Information has been extracted from a number of research papers and case studies including: Anderson (1982), Parkinson (1982b), Parkinson *et al.* (1981), Parkinson and Holder (1982), Prowse (1984, 1985b, 1986a, b) and Sherstone (1981).

Pre-break-up:

During the pre-break-up period, even before air temperatures rise above freezing, snow on the river ice and on land begins to melt under the influence of solar radiation. The onset of spring melt advances the break-up process in two ways. Firstly, snowmelt run-off produces increases in discharge, velocity and water levels and secondly, heat exchanges at both the snow-air and ice-river water interfaces result in melt of the river snow and ice cover, decreasing both its thickness and mechanical strength.

Although the transfers of sensible and latent heat by convection and conduction, and radiative heat are all important to the thermal ripening and melt of ice, it is radiation which can produce the largest and most dramatic changes in the mechanical strehgth of an ice cover. During the early spring, most heat supplied to the ice surface is consumed in the process of melt. Beginning with a fresh snowcover, much of the incoming short wave radiation is reflected from the surface. However, as the surface snow ages and ripens, the albedo decreases thereby allowing a larger percentage of the incoming radiation to penetrate into the underlying ice and snow. Once the snow cover is totally eliminated and the underlying ice sheet becomes exposed, radiative losses due to reflection may still be quite large if the top of the ice sheet is comprised of relatively opaque "white ice" forms (see Adams, 1976 and Michel, 1971 for description of ice types). However, once the relatively transparent layers of columnar black ice become exposed, significant amounts of short wave radiation can penetrate deep within the ice sheet.

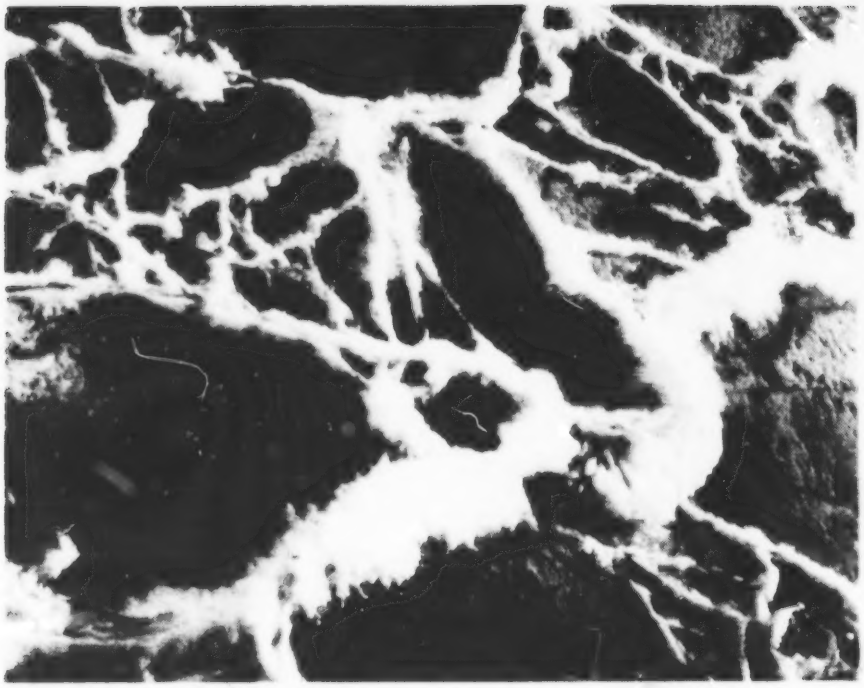

Fig.4. Break-up of thermally decayed black ice sheet. Individual black ice crystals are being extruded at floe boundaries

Fig.5. Break-up of competent ice sheet

Much of the light attenuated within black ice is absorbed at inter-crystalline boundaries; zones where there is a concentration of impurities deposited during the freeze-out process. Radiation absorbed in these zones causes a localised warming and an eventual melt of the crystal perimeters, a process termed "candling' The low structural integrity of this ice is apparent in Fig.4 which depicts the disintegration of a thermally weakened ice sheet. For comparison, a more competent ice sheet is shown fracturing in Fig.5.

During the pre-break-up period, melt may also occur at the base of the ice sheet. Although the temperature of the river water may only be a fraction of a degree above freezing, high flow velocities promote a rapid transfer of heat to the ice cover. From a study of pre-break-up conditions on the Liard River, Marsh and Prowse (1987) found that the hydrothermal heat transfer to the ice cover increased from approximately 10 W/m^2 one week before break-up to almost 100 W/m^2 immediately preceding break-up. The dramatic increase was largely ascribed to a rise in water temperature associated with break-up advance (Fig. 6). The water to ice heat transfer can be further increased by the formation of ice ripples (Fig.7) which increase subsurface turbulence and the related heat transfer coefficient. For example, Ashton and Kennedy (1972) and Gilpin *et al.* (1980) found that heat transfer was 50 to 60% greater for rippled ice surfaces than for smooth ice.

During the pre-break-up phase, the above hydrothermal processes may result in the appearance or increase in size of open water zones, thinning of ice in snow-free sections and a decrease in the load of snow on the river. However, from the point of view of break-up, the most important feature of this period is the increase in river flow which increases both water levels and downstream forces applied to the ice cover. In response, the ice begins to crack in patterns determined by its non-uniform thickness, strength and bonds to the banks and bed.

As the ice cover is buoyed by the rising water, it is essentially subjected to an upward loading. In many cases, the ice sheet first rises along near-vertical "hinge cracks" that formed either from ice shoving during freeze-up or from the vertical failure of the ice sheet during the winter recession in water levels (Fig.8). Although the centre portion of the ice sheet may rise, strips of ice on the bank-side of the hinge crack remain frozen to the bed and become inundated with river water and run-off from adjacent slopes. The term "shore lead" is often used to describe the accumulation of water along the banks.

For all unregulated rivers, the pre-break-up phase will normally develop to at least the above conditions. With further warming, the shore ice will completely melt or detach from the shore material. Similarly, the central portion of the ice sheet will detach from the banks and, with the increase in river width resulting from rising water levels, begin to shift within the

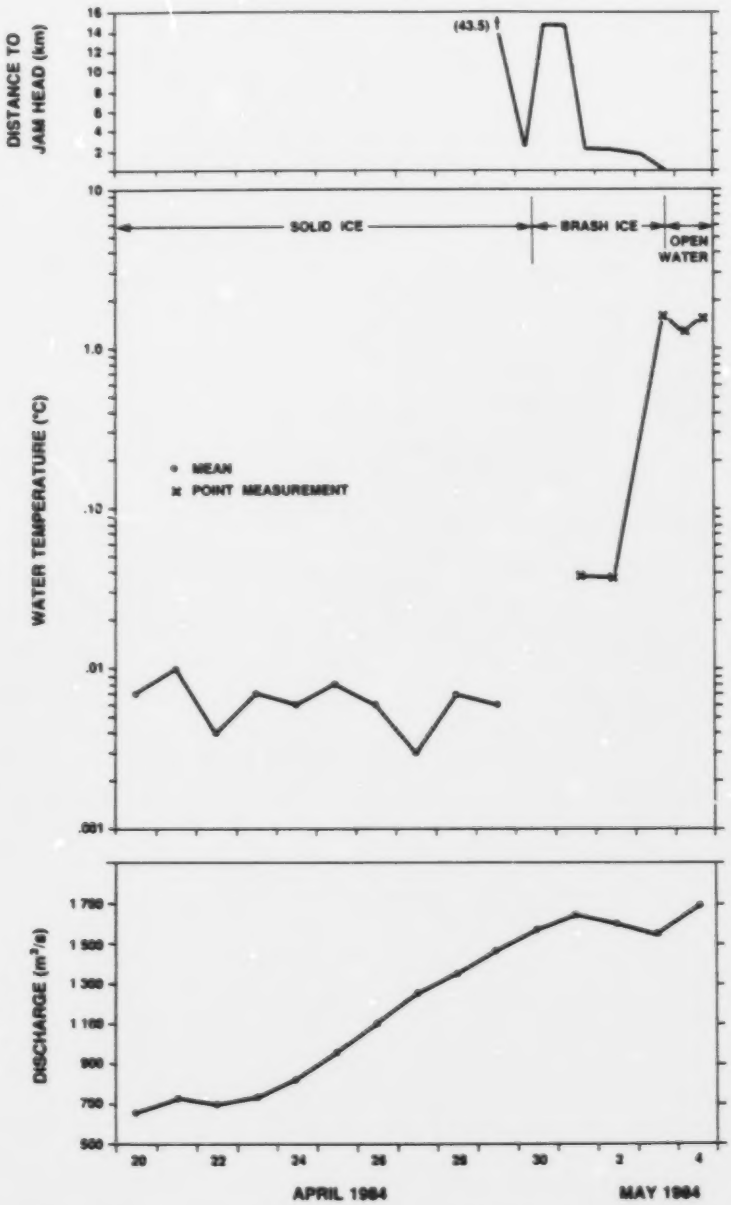

Fig.6. Water temperature and discharge associated with break-up advance (from Marsh and Prowse, 1987)

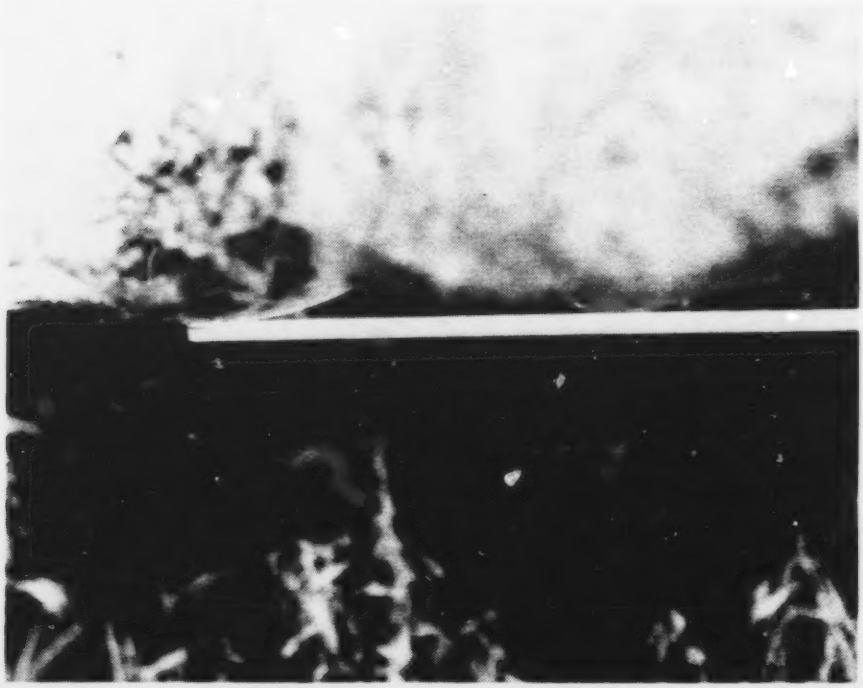

Fig.7. Ice ripples formed by thermal erosion at the base of an ice sheet

channel. This is often the period when transverse cracks (Fig.9) have been reported to appear. Tensile stresses caused by bending are the most probable mechanism of fracture (Beltaos, 1985).

While the major stem of the river remains largely ice covered, ice from smaller tributaries, which are more quickly affected by snowmelt run-off, drives down to accumulate at the tributary junction with the main stem (Fig. 10a). In other small tributaries where run-off is rapid yet the ice cover remains intact, often frozen directly to the bed, water may flow over the ice and directly on to the main ice sheet (Fig.10b). At the end of the pre-break-up phase, hydromechanical and hydrothermal action may have created open water zones, primarily at rapids sections and near tributary mouths, but most of the river remains covered by a substantial ice cover.

Break-up:

Although break-up has effectively occurred at a number of specific sites (eg. high velocity reaches) in the above discussion, it is just being initiated at the larger river scale. This next stage, which has been aptly referred to as the "drive" (Michel, 1971), is characterized by the continued increase in discharge as snowmelt accelerates but may also be marked by interruptions to

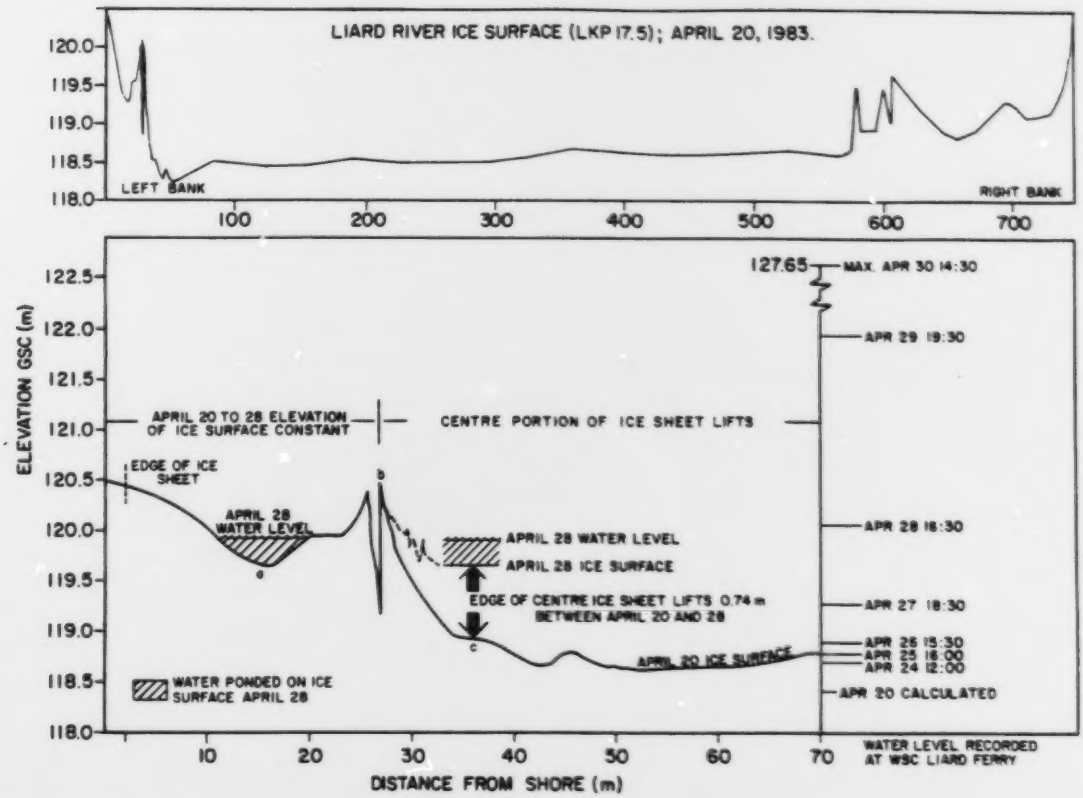
LIARD RIVER ICE SURFACE (LKP 17.5); APRIL 20, 1983.
LEFT BANK
RIGHT BANK
ELEVATION GSC (m)
DISTANCE FROM SHORE (m)
APRIL 20 TO 28 ELEVATION OF ICE SURFACE CONSTANT
CENTRE PORTION OF ICE SHEET LIFTS
EDGE OF ICE SHEET
APRIL 28 WATER LEVEL
APRIL 28 ICE SURFACE
EDGE OF CENTRE ICE SHEET LIFTS 0.74 m BETWEEN APRIL 20 AND 28
APRIL 20 ICE SURFACE
WATER PONDED ON ICE SURFACE APRIL 28
127.65 MAX. APR 30 14:30
APR 29 19:30
APR 28 18:30
APR 27 18:30
APR 26 15:30
APR 25 18:00
APR 24 12:00
APR 20 CALCULATED
WATER LEVEL RECORDED AT WSC LIARD FERRY

Fig.8. Ice lift along a hinge crack. Upper diagram shows entire river cross-section with hinge cracks at both banks. A large scale view of the left bank hinge crack is shown in the bottom diagram. Note the rise of the centre ice sheet between April 20 and April 28 and inundation of the shore fast ice. (from Prowse, 1984)

flow created by ice jams. The drive stage can best be illustrated by considering two extremes in break-up conditions, "pre-mature" or "mechanical" and "over-mature" or "thermal".

The two classifications refer to specific combinations of river discharge and ice strength, both of which are largely determined in the pre-break-up period. In the thermal case, which most closely approximates break-up conditions on lakes, spring discharge remains small while the ice sheet melts and is thoroughly weakened by thermal exchanges. This type of situation usually occurs in years or regions, where the winter snow accumulation is small and makes only limited and gradual contributions to spring run-off. Eventually the ice sheet will weaken to a state where it can easily be carried downstream even under low flow conditons. The term 'drive' barely applies in a situation of over-mature break-up.

Fig.9. Transverse crack formed in otherwise intact ice sheet

For the pre-mature case, conditions are reversed to include a strong, competent ice cover which may still be strongly attached to the shore, and a large, spring flood wave that is usually created by rapid and extensive snow-melt, sometimes augmented by rainfall. With rising discharge, the downstream forces become sufficient to rupture and dislodge the intact ice sheet driving it downstream. Initiation of this phase is often characterized by large hummocks or debacles formed by compressive forces between large ice sheets. Fig.11 illustrates the formation of a large hummock where two sheets have come into contact over a shoal location. Note the extent of bending in the intact ice sheet at the upstream base of the hummock.

Prowse (1986a) notes that both thermal and mechanical break-ups have occcurred on the Liard River between 1978-1984. Mechanical break-ups were the most common, occurring in all years except 1980 and 1984. The downstream advance of a mechanical break-up was dominated by a sequential, downstream progression of a localised zone of ice fracturing and ice clearance which took from 4 to 8 days to travel from Nelson Forks to the Liard River mouth (0.6 - 1.2 m/s). In these years, the ice cover displayed little evidence of thermal decay or mechanical weakening before the arrival of the break-up front. Other

Fig.10a. Ice jam formed at tributary mouth against intact ice sheet of larger order river

than shore leads, zones of open water were generally restricted to large shoal areas or high velocity reaches. Most tributaries were ineffective in cutting open water channels into the main ice sheet and instead either jammed at their mouths or spilled ice and water out onto the surface of the Liard ice cover.

Within many reaches, the break-up zone rapidly advanced along a single front at which the intact ice sheet was fractured - almost pulverized - into small diameter floes such as those shown in Fig.12. The front was followed by a large mass of this fractured ice, which extended tens of kilometres up-stream, and finally by the leading edge of open water. The rate of advance of these break-up fronts often exceeded normal open water velocities. In the 1983 break-up, for example, the break-up front approached the Liard River mouth at an average velocity (measured over an 18 km distance) of just over 5 m/s (Prowse, 1984). Similar velocities have been observed on other large

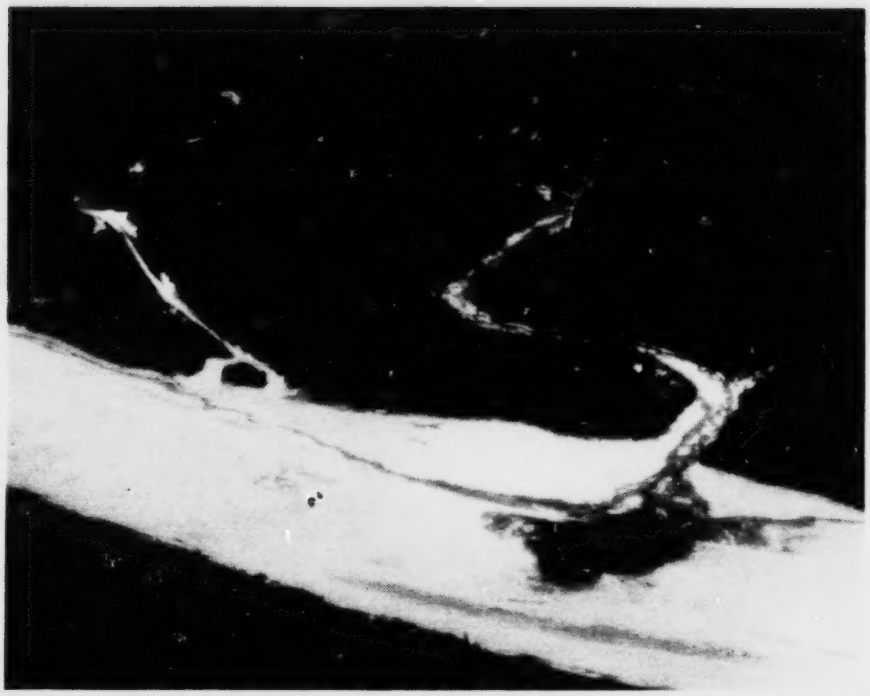

Fig.10b. Ice and water from break-up of tributary spilling onto the intact ice sheet of larger-order river

Fig.11. Hummock formed by downstream forces of advancing break-up front (background). Flow is from left to right. Note bending of ice sheet at the upstream end of the hummmock. Exposed portion of ice sheet is approximately 0.7 m thick

Fig.12. Rapid fragmentation of ice sheet associated with advance of mechanical break-up front. Note water spilling onto intact ice sheet

northern Canadian Rivers (Doyle, 1977; Doyle and Andres, 1978; Gerard, 1975; Gerard *et al.*, 1984; Parkinson, 1982a) and have generally been ascribed to surges resulting from the failure of upstream ice jams.

The ice clearance patterns associated with the 1980 and 1984 thermal break-ups differed considerably from those of the other five years. Although a general downstream progress in ice clearance occurred at a basin-wide scale, more locally the advance of break-up was relatively haphazard. In many instances, a number of break-up fronts were simultaneously active within different portions of the river. Many of the break-up fronts had been initiated by flow in high velocity zones or by flow from major tributaries. The ease with which contributing flow could fracture and move the ice cover was partly dependent on the amount of prior thermal weakening of the ice. Even the structure of the advancing fronts differed from those in Fig.12. Most were comprised of very large diameter floes and only at a considerable distance upstream of the front was the ice cover finally reduced to small brash ice. In some locations the ice sheet almost melted *in situ* (Fig.13).

Fig.13. *In situ* **thermal decay ice sheet during thermal break-up**

A major factor controlling the pattern of break-up was the degree of pre-break-up thermal decay. A simple measure of the amount of atmospheric heating can be obtained from a surrogate heat index, such as degree days. Table 1 lists the number of accumulated degree days (ADD; °C) from April 1 to the day of break-up for the years 1978 to 1984 at Fort Simpson. The relatively high degree of atmospheric heating of the ice cover which occurred prior to break-up in 1980 and 1984 is reflected in ADD totals of +149 and +71 for these two years of thermal break-up. The other five years of mechanical break-up produced only negative ADD totals, ranging from -174 to -56.

Ice Jams:

As is the case for most northern rivers, ice jams are a regular feature of the Liard River break-up. Based on observations via aerial reconnaissance and satellite imagery (Fig.14), Sherstone (1981) concluded that the highest frequency of jamming occurs on the lower Liard in a 25-km reach approximately 100 km upstream of the river mouth and in the lower 60 km of the river. One particular location, at the confluence of the Liard and Mackenzie Rivers, has

Table 1. Accumulated degree days (Celsius) from April 1 to day of break-up (from Prowse, 1986a)

Breakup year	Date	Accumulated deg. days *	Discharge (m^3/s) +
1978	May 03	-61.7	2270
1979	May 11	-174.2	900
1980	May 02	+149.1	1700
1981	May 07	-73.0	2800
1982	May 09	-55.7	1000
1983	Apr 29	-48.3	1450
1984	Apr 29	+70.8	1460

* Meteorological data from Fort Simpson Airport, 2 km from Liard River WSC station.
\+ Mean daily discharge.

also been identified by MacKay and Mackay (1973b) to be a site of recurrent and often spectacular ice jamming. Ice jams at the Liard River mouth are typical of jams that form on rivers which flow into lakes or rivers that break-up later. Unlike ice jams which tend to form randomly, for example at irregular intervals and locations in the vicinity of channel restrictions or low velocity reaches, the river mouth or delta type of ice jam regularly develops at approximately the same location. This is apparent in Fig.15 which shows the regular position of the ice jam toe (downstream end) across the Liard River mouth. Table 2 summarizes the dimensions of these jams, which range in length from 9.5 to 22.1 km and in area from 10.0 to 22.8 km^2.

Despite the regularity in location and similarity in area, the jams differed in other important characteristics, such as surface composition, thickness and effect on water levels. As noted by Prowse (1986a), these differences are largely related to the type of break-up which lead to jam formation. First, consider the surface composition. In the years of mechanical break-up, the ice jam toe was often comprised of small diameter floes butting against a relatively intact ice cover; a physical situation resembling that of the moving break-up front in Fig.12. Futhermore, almost the entire surface area of all the mechanical jams consisted of small diameter brash ice. In contrast, the toe and upstream portions of the thermal jams were dominated by large floes some of which bridged the entire river cross-section. The relative lack of small diameter brash ice in the thermal jams is indicative of the absence of a dynamic break-up front that was present in the mechanical break-ups.

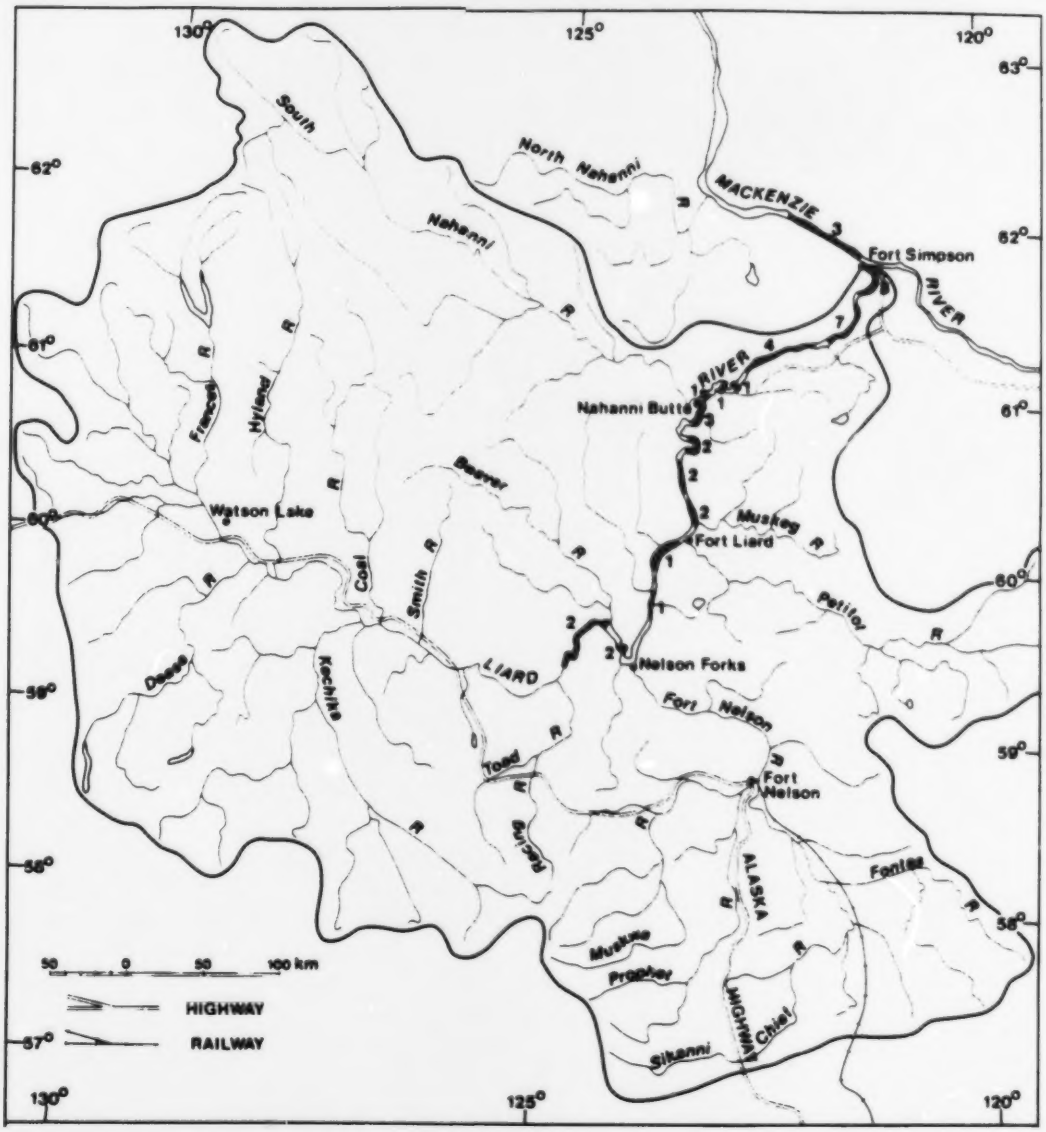

Fig.14. Location and frequency of ice jamming observed from satellite over the period 1973-1978 (from Sherstone, 1981)

There are also distinct differences in the thickness of the ice accumulations. Although *in situ* measurement of jam thickness is nearly impossible, considerable information has been gathered about the vertical dimensions of shear walls which Calkins (1983) and Beltaos (1983a) suggest as surrogate measures of jam thickness. In years of mechanical break-up, shear walls ranging from 4-8 m remained along the banks of the ice-jam reach (Anderson, 1982; Parkinson *et al.*, 1981; Prowse, 1984, 1986b; Sherstone, 1981). Fig.16 shows the magnitude of such walls recorded during the 1983 mechanical event.

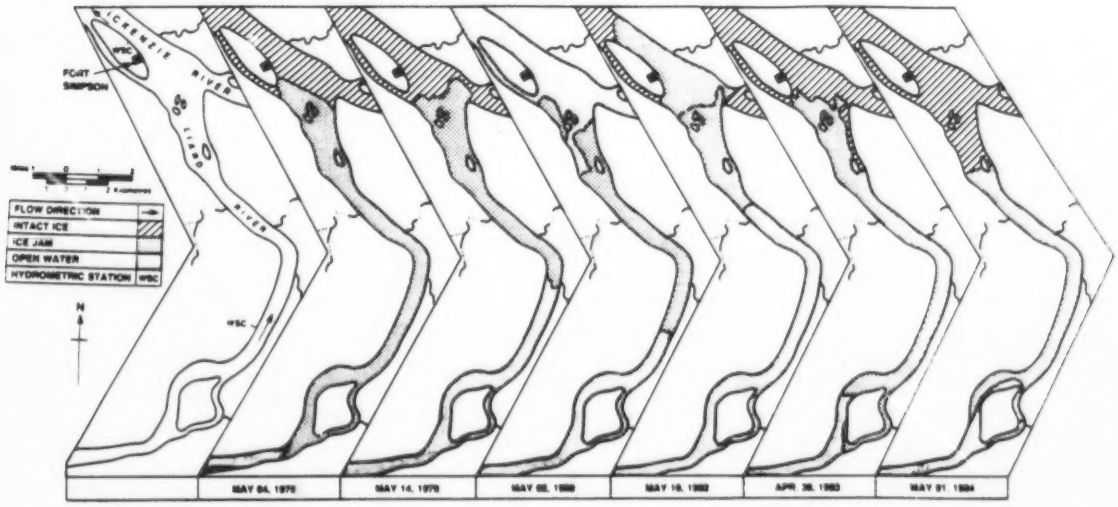

Fig.15. Position of ice jams at the Liard River mouth (from Prowse, 1986a)

Table 2. Ice jam characteristics (from Prowse, 1986a)

Year	Date	Length (km) *	Area (km^2) +	Discharge (m^3/s) #
1978	May 04	22.1	22.8	3110
1979	May 14	12.1	11.7	1850
1980	May 02	9.5	10.0	1700
1982	May 10	17.8	10.8	1500
1983	Apr 30	19.1	19.2	1750
1984	May 01	11.0	13.1	1680

* measured along the centre of the ice covered channel
\+ excluding areas of open water
\# mean daily discharge

Much smaller shear wall heights characterized the 1980 and 1984 thermal events. Within some zones the walls reached a height of 2-2.5 m but, over much of the reach, remnant shore ice was only the thickness of the original ice sheet.

Based on the surface area and thickness information obtained for the 1983 ice jam, which was classed as a large event, Prowse (1986a) estimated the ice volume within the jam to be 64.4 X $10^6 m^3$. In terms of ice contained within the pre-break-up ice cover, this represents only 19% of the ice downstream of Nelson Forks, or approximately the lower 89 km of the river. This distance is even less than the 150 km which the break-up front travelled in the 24 hr

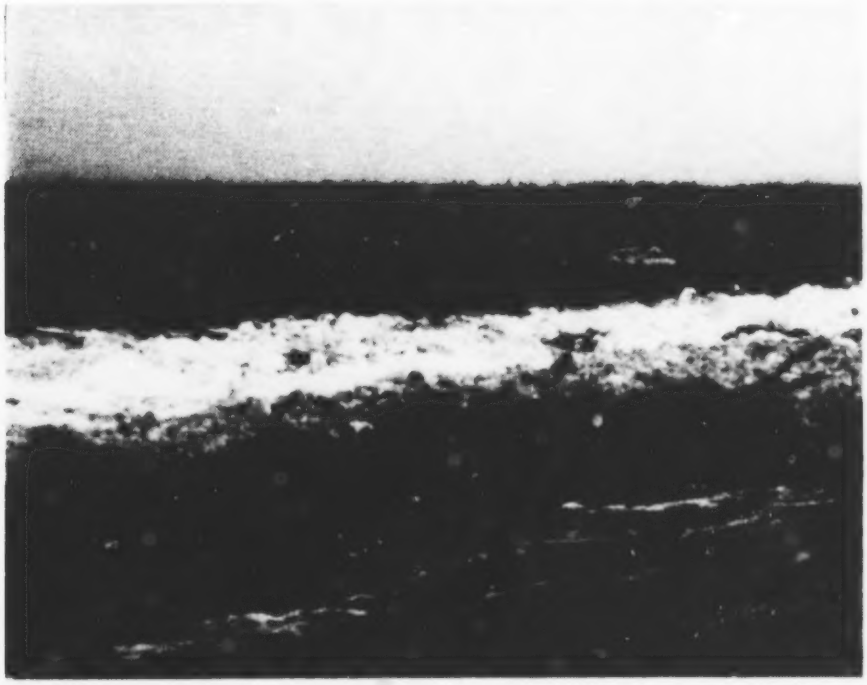

Fig.16. Shear walls remaining after ice jam release, Liard River mouth

period preceding the ice jam event. Thus, even within one day, almost 40 percent of the pre-break-up ice cover was either stranded on the shores, melted during downstream travel or was sufficiently fragmented to pass under the jam. More importantly, the results suggest that recent large events, as exemplified by the 1983 jam, have developed from only a limited amount of the total available ice supply. Much longer ice jams could therefore be expected to develop given hydrologic and meteorologic conditions more favourable to the rapid downstream transport of ice. More generally, high ice losses can be expected for long river reaches with many tributaries, whereas much smaller losses are typical of shallow, steep rivers where the ice-contributing area is small (U.S. Army, 1982).

Marsh and Prowse (1987) point to the significance of hydrothermal melt in removing ice during the break-up period. Fig.6 shows the rapid rise from near 100 W/m^2 immediately prior to break-up, to over 10,000 W/m^2 following fragmentation and subsequent jamming of the ice. Hydrothermal melt has also been shown by Prowse and Marsh (1985) to be important in the ablation of the 1983 ice jam at the Liard mouth, which decreased in length from approximately 23 km to only 6 km within a five day period (Fig.17).

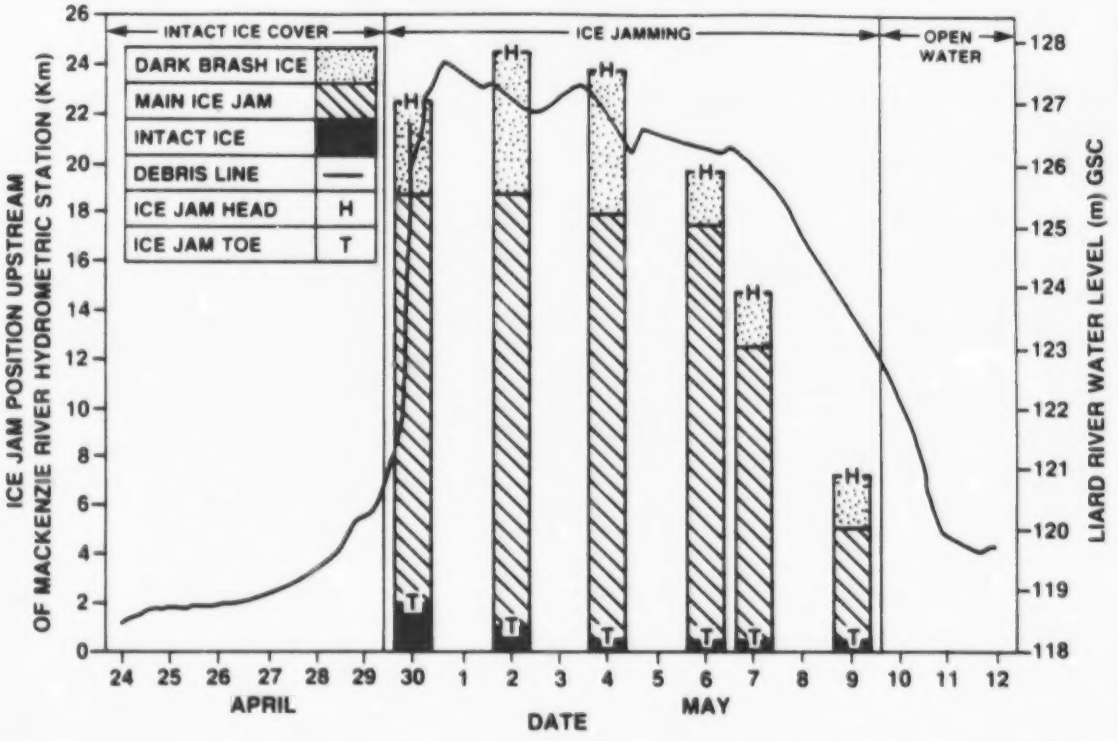

Fig.17. Shrinkage of ice jam due to thermal decay (after Prowse and Marsh, 1985). Note rapid decline in water levels associated with the decrease in jam length

The dramatic rise in hydrothermal heat flow which accompanies ice break-up is due not only to the rough subsurface enhancing the water-ice heat transfer but also to a rise in water temperature. Given the same meteorological conditions, the greatest rise in water temperature should occur during mechanical break-ups in which upstream reaches have been largely cleared of floating ice thereby permitting uninterrupted heating of the flow. Reduced heating and lower temperatures will prevail in thermal break-ups which leave upstream zones of alternating ice cover and open water.

Water Levels and Discharge:

Water stage data have been collected near the Liard River mouth by the Water Survey of Canada since 1972. As for most northern rivers, numerous gaps exist in the record because of frequent ice damage to recording instruments during the break-up period. However, since 1978 special efforts have been made to record maximum stage produced by ice conditions. Table 3 lists the maximum stages during both the open water and ice conditions periods for the years

Table 3. Annual maximum water levels during ice and open water conditions (from Prowse, 1986a)

Year	ICE CONDITIONS Date	Stage (m amsl)	Discharge (m^3/s)*	OPEN WATER Date	Stage (m amsl)	Discharge (m^3/s)*
1978	May 03	125.25	2270	June 11	120.89	6116
1979	May 14	125.15	1850	July 07	123.66	13300
1980	May 01	121.38	1550	June 12	121.35	7130
1981	May 07	128.20	2800	May 31	122.89	11500
1982	May 10	126.91	1500	May 21	123.65	12900
1983	Apr 30	127.65	3971	June 05	121.86	8400
1984	May 01	122.19	1640	June 12	122.61	10900
MEAN 1978-1984		125.24	1909	-	122.42	10035

* mean daily discharge except 1983 which is an instantaneous value
\+ instantaneous discharge

1978-84. Notably, except for 1984, all annual maximum stages were measured during the period of river ice break-up and not during the open-water period.

Based on evidence from aerial photographs and field surveys, the high stage in these years can be directly attributed to conditions created by ice jams at the Liard River mouth. Given the location of the Liard hydrometric station relative to the ice jams (Fig.15), the stage records are considered to be representative of conditions found within the upper portions of the ice accumulation or slightly upstream of the jam head (upstream end of ice accumulation). Characteristics of the jams provided in Table 2 and Fig.15 refer to the same day as, or at most one day after, the recording of the respective maximum water levels.

As evident in Table 3, there is a noticeable difference in water levels between thermal and mechanical break-ups. The 1980 and 1984 ice jams produced relatively low water levels of 121.38 and 122.19 m a.m.s.l., while the maximum stage from the other five jams ranged from 125.15 to 128.20 m a.m.s.l. All other factors being equal, this contrast in water levels between mechanical and thermal break-up jams can be largely explained by differences in ice jam thickness and subsurface roughness. The thermal jams are not only thinner but the subsurface roughness of the large floes is small relative to that of heavily fragmented ice. The combined effect of a low ice thickness to flow depth ratio and small subsurface roughness presents a much smaller resistance to flow through the jam section than that of the thick, rough ice accumu-

lations typical of the mechanical ice jams. The higher the flow resistance, the higher the backwater levels will be for a particular discharge.

Discharge, however, also varied among jams. Inspection of Table 3 reveals that, even when comparing years of mechanical break-ups, different water levels occurred with similar flows. These variations can be partly explained by differences in physical conditions of the mechanical jams, but the situation is complicated by the quality of discharge information (Prowse *et al.*, 1987). During break-up, ice conditions are so variable that no consistent relationship can be established between stage and discharge. To circumvent this problem, a standard practice used on northern rivers is to estimate mean daily discharge figures by extrapolating flow data from upstream ice-free sites to the downstream ice-affected reaches. Allowances are made for flow travel time and hydrometeorological events such as snowmelt and rainfall. However, a major drawback of this approach is the difficulty in accounting for rapid fluctations in flow and water levels which occur on time frames of much less than one day. Hence, mean daily discharge figures are of limited use for analyzing break-up water levels.

One method by which maximum water levels can be estimated for ice jams which form under a range of flow conditions is offered by the theory of wide channel equilibrium jams (Pariset *et al.*, 1966; Uzuner and Kennedy, 1976; Beltaos, 1983a). Prowse (1986a) used this technique for analyzing the Liard River jams. Assuming that equilibrium jams formed at different levels of discharge would have similar physical characteristics, the stage-discharge curve in Fig.18 was developed. Also shown is a stage-discharge relationship based on a simplified method described by Beltaos (1983a). Although both approaches predict dramatic increases in stage of approximately 4-8 m above those which would result from equivalent discharge under open water conditions, neither curve forms an upper envelope to all the ice jam events. However, only the 1983 event is plotted using an instantaneous discharge. The remaining points are referenced to mean daily discharge figures. Much greater discharge may have been responsible for the observed jam stages and could result in the events falling on or below the ice jam rating curves. The major obstacle to using the equilibrium jam theory for predicting both the magnitude and frequency of high stages on northern rivers is simply the lack of useable discharge information.

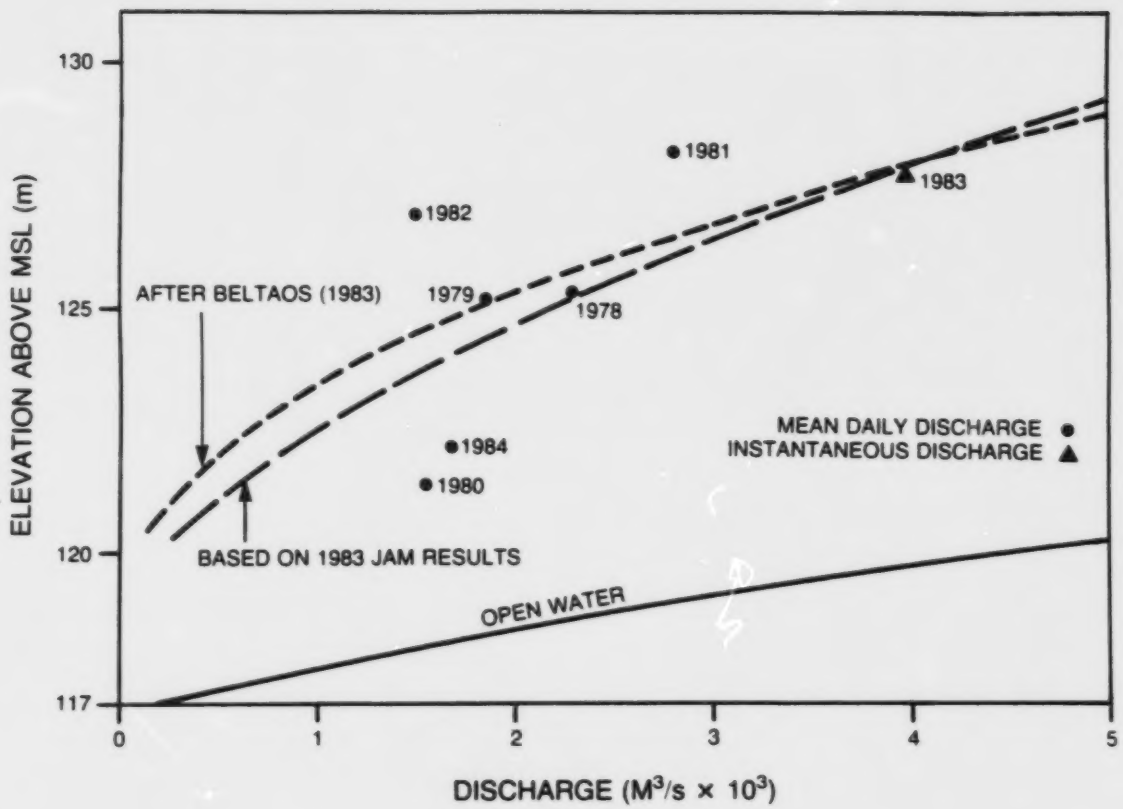

Fig.18. Open water and ice jam stage-discharge relationships for the Liard River mouth. (from Prowse, 1986a)

DISCUSSION

As an introduction to break-up on northern rivers, the above material was structured as a sequence of processes from tne early stages of melt to ice-clear conditions. There are, however, numerous gaps in our understanding of break-up processes, some simply due to the lack of relevant, quantitative field data. In recognition of this, the NRCC Working Group on River Ice Jams has developed a set of guidelines for river ice monitoring programs (Prowse, 1985a) and for the extraction of break-up data from existing hydrometric records (Beltaos, 1983b). To improve our ability to deal with river ice problems, there is also a range of specific research needs which should be addressed. The following details a few of the more pressing of these.

One of the most important changes which occurs during the pre-break-up period is the decrease in the ability of an ice cover to resist downstream

forces. Although the general effect of the major heat flows on the structural integrity of an ice sheet are known, a technique does not yet exist to accurately predict changes in ice strength from standard meterological variables. Moreover, the importance of internal ice strength relative to other factors that determine the overall cover stability, such as attachment to the banks, remains unknown. The ability to predict changes in ice strength will also allow the forecasting of the overall severity of break-up, as evinced by the strong contrasts between mechanical and thermal break-ups on the Liard River.

In the past few years, significant advances have been made in our understanding of some of the large-scale fracturing processes which accompany break-up but questions remain about what controls the rapid fragmentation of ice associated with mechanical break-up fronts. More generally, research should be focussed on explaining the surge-stall behaviour of break-up advance. Surges are thought to be released by the sudden failure of upstream ice jams and to produce rapidly moving break-up fronts, but little is known about the conditions leading to jam failure or those that dampen the downstream passage of the surge and eventually lead to stalling of the break-up front and formation of another jam. Explanations of the stalling behaviour is a key to forecasting the initiation of jams that form more randomly in time and space than the delta-type of jam, as described for the Liard River mouth.

One of the more readily justifiable reasons for conducting research on river ice is the high damage costs which result from backwater flooding created by ice jams. Since the mid-1960's, the theory of equilibrium jams has evolved as an effective tool for predicting the maximum stage which would result from ice jams under varying discharge. However, the development of frequency-stage curves for ice jams has been thwarted by the inability to accurately calculate the frequency and magnitude of discharge which leads to jam formation. A number of approaches have been suggested for improving the measurement of discharge during the break-up period (Prowse *et al.*, 1987) but improvement of the forecasting of break-up discharge will require a number of major research advancements. First, a model of break-up advance will have to be developed based on an improved understanding of the surge-stall behaviour of break-up. In conjunction, a flow routing model also needs to be developed which takes into account the large and rapid fluctuations in discharge which characterize the surge-stall style of break-up. In order to provide input to

these two models, they will have to be interfaced with existing snowmelt and run-off models. It should then be possible to predict the downstream passage of flow under break-up conditions and, with existing ice jam-stage models, predict potential flooding. Frequency predictions of stage will, however, still require probability estimation of jam formation and run-off magnitude.

Given the complexities of developing and linking the above models, development of stage-frequency curves for break-up conditions should be considered a long-term objective but one that is essential if effective flood damage reduction is to be achieved on northern rivers.

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